Ultra High Energy Cosmic Radiation: Experimental and Theoretical Status

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Abstract. We give a brief overview of the current experimental and theoretical status of cosmic rays above $\sim 10^{17}$ eV. We focus on the role of large scale magnetic fields and on multi-messenger aspects linking charged cosmic ray with secondary $\gamma-$ray and neutrino fluxes.

INTRODUCTION

High energy cosmic ray (CR) particles are shielded by Earth's atmosphere and reveal their existence on the ground only by indirect effects such as ionization and showers of secondary charged particles covering areas up to many km^2 for the highest energy particles. In fact, in 1912 Victor Hess discovered CRs by measuring ionization from a balloon [1], and in 1938 Pierre Auger proved the existence of extensive air showers (EAS) caused by primary particles with energies above 10^{15} eV by simultaneously observing the arrival of secondary particles in Geiger counters many meters apart [2].

After almost 90 years of research, the origin of cosmic rays is still an open question, with a degree of uncertainty increasing with energy [3]: Only below 100 MeV kinetic energy, where the solar wind shields protons coming from outside the solar system, the sun must give rise to the observed proton flux. Above that energy the CR spectrum exhibits little structure and is approximated by broken power laws $\propto E^{-\gamma}$: At the energy $E \simeq 4\times 10^{15}$ eV called the "knee", the flux of particles per area, time, solid angle, and energy steepens from a power law index $\gamma \simeq 2.7$ to one of index $\simeq 3.0$. The bulk of the CRs up to at least that energy is believed to originate within the Milky Way Galaxy, typically by shock acceleration in supernova remnants. The spectrum continues with a further steepening to $\gamma \simeq 3.3$ at $E \simeq 4\times 10^{17}$ eV, sometimes called the "second knee". There are experimental indications that the chemical composition changes from light, mostly protons, at the knee to domination by iron and even heavier nuclei at the second knee [4]. This is in fact expected in any scenario where acceleration and propagation is due to magnetic fields whose effects only depend on rigidity, the ratio of charge to rest mass, Z/A. This is true as long as energy losses and interaction effects, which in general depend on Z and A separately, are small, as is the case in the Galaxy, in contrast to extra-galactic cosmic ray propagation at ultra-high energy. Above the so called "ankle"

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or “dip” at $E \simeq 5 \times 10^{18}$ eV, the spectrum flattens again to a power law of index $\gamma \simeq 2.8$. This latter feature is often interpreted as a cross over from a Galactic component, which steepens because cosmic rays are not confined by the Galactic magnetic field any more or because Galactic sources do not accelerate beyond the ankle, to a harder component of extragalactic origin. However, the dip at $E \simeq 5 \times 10^{18}$ eV could also be explained by pair production by extra-galactic protons, if the extra-galactic component already starts to dominate below the ankle, for example, around the second-knee [5] at a few times 10^{17} eV. This requires a relatively steep injection spectrum $\propto E^{-2.6-2.7}$. Below a few times 10^{17} eV this extra-galactic component would become unobservable at Earth due to diffusion in extra-galactic magnetic fields (EGMF) [6]. In addition, the effective volume-averaged injection spectrum has to become flatter somewhere below $\sim 10^{18}$ eV in order to avoid excessive power going into cosmic rays and to avoid overproduction of GeV–TeV $\gamma-$rays from pp interactions with the ambient gas.

The low cross-over scenario also requires the dominance of protons around the dip. Theoretically, this can be achieved either because preferentially protons are accelerated or because extended EGMF lead to strong photo-spallation during propagation [7]. Experimentally, above $\simeq 10^{17}$ eV the chemical composition is basically unknown [8]. Around 10^{18} eV the situation is particularly inconclusive as HiRes [10] and HiRes-MIA [11] data suggest a light (proton dominated) composition, whereas other experiments indicate a heavy composition [4]. In any case, the cosmic ray flux should be extra-galactic at least above the ankle, where a galactic origin would predict an anisotropy toward the galactic plane because galactic magnetic fields can no longer isotropize the cosmic rays. No such anisotropy is seen. There are also experimental indications for a chemical composition becoming again lighter above the ankle, although a significant heavy component is not excluded and the inferred chemical composition above $\sim 10^{18}$ eV is sensitive to the model of air shower interactions and consequently uncertain presently [8]. In addition, should a substantial heavy composition be experimentally observed up to the highest energies, some sources would have to be surprisingly nearby, within a few Mpc, otherwise only low mass spallation products would survive propagation [9]. In the following we will restrict our discussion on extra-galactic ultra-high energy cosmic rays (UHECRs).

Although statistically meaningful information about the UHECR energy spectrum and arrival direction distribution has been accumulated [12], no conclusive picture for the nature and distribution of the sources emerges naturally from the data. There is on the one hand the approximate isotropic arrival direction distribution [13] which indicates that we are observing a large number of weak or distant sources. On the other hand, there are also indications which point more towards a small number of local and therefore bright sources, especially at the highest energies: First, the AGASA ground array claimed statistically significant multi-plets of events from the same directions within a few degrees [14, 13], although this is controversial [15] and has not been seen so far by other experiments such as the fluorescence experiment HiRes [16]. The spectrum of this clustered component is $\propto E^{-1.8}$ and thus much harder than the total spectrum [14]. Second, nucleons above $\simeq 70$ EeV suffer heavy energy losses due to photo-pion production on the cosmic microwave background (CMB) — the Greisen-Zatsepin-Kuzmin (GZK) effect [17] — which limits the distance to possible sources to less than $\simeq 100$ Mpc [18]. This predicts a “GZK cutoff”, a drop in the spectrum, whose strength depends on the source distribution and may even depend on the part of the sky one is looking at: The "cutoff" could be mitigated in the northern hemisphere where more nearby accelerators related to the local supercluster can be expected. Apart from the SUGAR array which was active from 1968 until 1979 in Australia, all UHECR detectors completed up to the present were situated in the northern hemisphere. Nevertheless the situation is unclear even there: Whereas a "cut-off" is consistent with the few events above 10^{20} eV recorded by the fluorescence detector HiRes [19], there is a tension with the 11 events above 10^{20} eV detected by the AGASA ground array [20]. Still, this could be a combination of statistical and systematic effects [21], especially given the recent downward revision of the energy normalization in AGASA [22]. The solution of this problem will have to await more analysis and more statistics and, in particular, the completion of the Pierre Auger project [23] which will combine the two complementary detection techniques adopted by the aforementioned experiments and whose southern site is currently in construction in Argentina.

ROLE OF LARGE SCALE MAGNETIC FIELDS

The hunt for UHECR sources is further complicated by the presence of large scale cosmic magnetic fields which may significantly deflect charged cosmic rays even at the highest energies, in particular if sources correlate with high magnetic field regions such as galaxy clusters. A major issue in UHECR propagation studies is, therefore, the strength and distribution of EGMF. It is known that galaxy clusters harbor magnetic fields of microGauss strength. Unfortunately, it is poorly known how quickly these fields fall off with increasing distance from the cluster center. The current data indicate that μG strength magnetic fields extend out to at least ~ 1 Mpc [24] and possibly to larger distances [25, 26]. At distances above 1 Mpc from a cluster core, however, probing the magnetic fields becomes extremely difficult because the Faraday Rotation Measure loses sensitivity in low density regions. Furthermore, the intracluster magnetic field topology is also poorly known, although the situation will likely improve in the future, for example with the advent of powerful radio astronomical instruments such as the square kilometer array.

One possibility in the meantime is to adopt large scale structure simulations (LSS) which include magnetic fields. However, different models for these fields tend to give different predictions for UHECR deflection, as the comparison between Refs. [27, 28] and Ref. [29] shows. In Ref. [27], the authors use magnetic fields derived from a cosmological LSS with magnetic fields generated at the shocks that form during LSS formation, whereas in Ref. [28] and Ref. [29] fields of "primordial" origin have been considered. While the different models for initial magnetic seed fields produce different large scale magnetic field distributions and, therefore, lead to different predictions for UHECR deflection, there is still a significant discrepancy between Ref. [27, 28] and Ref. [29], hinting that other technical reasons may play a role here. In the more extended fields from the simulations of Refs. [27, 28] deflection of protons up to 10^{20} eV can be up to tens of degrees, whereas deflections in the simulations of Ref. [29] are typically below a degree.

We recall that since acceleration is rigidity dependent, at the acceleration sites the highest energy cosmic ray flux is likely dominated by heavy nuclei. If this is indeed the case, it is interesting to point out that even in the EGMF scenario of Ref. [29], deflections could be considerable and may not allow particle astronomy along many lines of sight: The distribution of deflection angles in Ref. [29] shows that deflections of protons above 4×10^{19} eV of $\gtrsim 1^\circ$ cover a considerable fraction of the sky. Suppression of deflection along typical lines of sight by small filling factors of deflectors is thus unimportant in this case. The deflection angle of any nucleus at a given energy passing through such areas will therefore be roughly proportional to its charge as long as energy loss lengths are larger than a few tens of Mpc [30]. Deflection angles of $\sim 20^\circ$ at $\sim 4\times10^{19}$ eV should thus be the rule for iron nuclei. In contrast to the contribution of our Galaxy to deflection which can be of comparable size but may be corrected for within sufficiently detailed models of the galactic field, the extra-galactic contribution would be stochastic. Statistical methods are therefore likely to be necessary to learn about UHECR source distributions and characteristics as well as EGMF. For example, a suppressed UHECR arrival direction auto-correlation function at degree scales, rather than pointing to a high source density, could be a signature of extended EGMF [27].

Finally, EGMF can considerably increase the path-length of UHECR propagation and thus spectra, especially from individual sources, as well as the chemical composition observed at Earth [31].

MULTI-MESSENGER APPROACH: CHARGED PRIMARY COSMIC RAYS AND SECONDARY GAMMA-RAYS AND NEUTRINOS

The physics and astrophysics of UHECRs are also intimately linked with the emerging field of neutrino astronomy [33] as well as with the already well established field of $\gamma-$ray astronomy [34]. Indeed, all scenarios of UHECR origin, including the top-down models, are severely constrained by neutrino and $\gamma-$ray observations and limits. In turn, this linkage has important consequences for theoretical predictions of fluxes of extragalactic neutrinos above about a TeV whose detection is a major goal of next-generation neutrino telescopes: If these neutrinos are produced as secondaries of protons accelerated in astrophysical sources and if these protons are not absorbed in the sources, but rather contribute to the UHECR flux observed, then the energy content in the neutrino flux can not be higher than the one in UHECRs, leading to the so called Waxman-Bahcall bound for transparent sources with soft acceleration spectra [35, 36]. If one of these assumptions does not apply, such as for acceleration sources with injection spectra harder than E^{-2} and/or opaque to nucleons, or in the top-down scenarios where X particle decays produce much fewer nucleons than $\gamma-$rays and neutrinos, the Waxman-Bahcall bound does not apply, but the neutrino flux is still constrained by the observed diffuse $\gamma-$ray flux in the GeV range.

Fig. 1 provides a sketch of "realistic" cosmic ray, $\gamma-$ray, and neutrino flux predictions in comparison with experimental observations, limits, and sensitivities. It shows a theoretical scenario in which extra-galactic cosmic ray sources roughly evolving as quasars

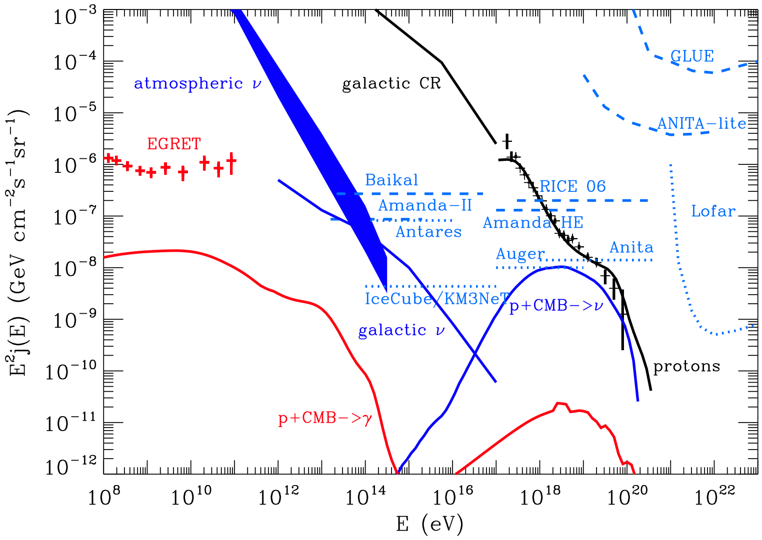

FIGURE 1. Model fluxes (multiplied by the squared energy) compared to experimental data, limits and sensitivities. Primary cosmic ray fluxes (data and a model, see text) are shown in black, the secondary $\gamma-$ray flux expected from proton interactions with the CMB and infrared background in red and the "guaranteed" neutrino fluxes per neutrino flavor in blue: atmospheric neutrinos, galactic neutrinos resulting from cosmic ray interactions with matter in our Galaxy, and "GZK" neutrinos resulting from cosmic ray interaction with the CMB and infrared background. These secondary fluxes depend to some extent on the distribution of the (unknown) primary cosmic ray sources for which active galaxies were assumed above 10^{17} eV. The flux of atmospheric neutrinos has been measured by underground detectors and AMANDA. Also shown are existing upper limits and future sensitivities to diffuse neutrino fluxes from various experiments (dashed and dotted light blue lines, respectively) [33], assuming the Standard Model neutrino-nucleon cross section extrapolated to the relevant energies. The maximum possible neutrino flux would be given by horizontally extrapolating the diffuse $\gamma-$ray background observed by EGRET [32].

inject a spectrum $\propto E^{-2.6}$ of dominantly protons down to $\sim 10^{17}$ eV where a cross-over to galactic cosmic rays occurs [5]. The "cosmogenic" neutrino flux produced by protons interacting with the low energy photon background can in principle be used to test these assumptions on which it depends considerably [37].

3-dimensional propagation in structured large scale magnetic fields also has considerable influence on secondary $\gamma-$ray and neutrino fluxes. Fig. 2 demonstrates how magnetic fields of micro-Gauss strength surrounding a UHECR source, for example in a galaxy cluster, can influence the secondary GeV-TeV $\gamma-$ray fluxes produced by electromagnetic cascades initiated by UHECR interactions with the CMB and infrared background. This is the result of simulations with our public code CRPropa [38], discussed in Ref. [39, 40]. For the steep injection spectrum $\propto E^{-2.7}$ assumed in Fig. 2, the photon flux below a TeV is dominated by synchrotron radiation from electron/positron pairs produced by protons around the ankle. As a consequence, it depends considerably on strength and extension of the magnetic field. We note that apparently time-variable fluxes of order $(3-10)\times10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ above 730 GeV, concentrated within $\sim 0.2^\circ$ of M87 in the Virgo cluster at $\sim 16\,$Mpc, have been seen by HEGRA and HESS [41]. A flux of $\sim 5\times10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ above 1 TeV, extended over a few degrees around the active galactic nucleus 1ES 1959+650 at $\simeq 200\,\mathrm{Mpc}$, has recently be seen by MAGIC [42]. The spectra tend to be considerably steeper than E^{-2}. Since the fluxes are comparable to the predictions in Fig. 2, these observations indeed start to constrained the contribution of sources immersed in galaxy clusters to the UHECR flux.

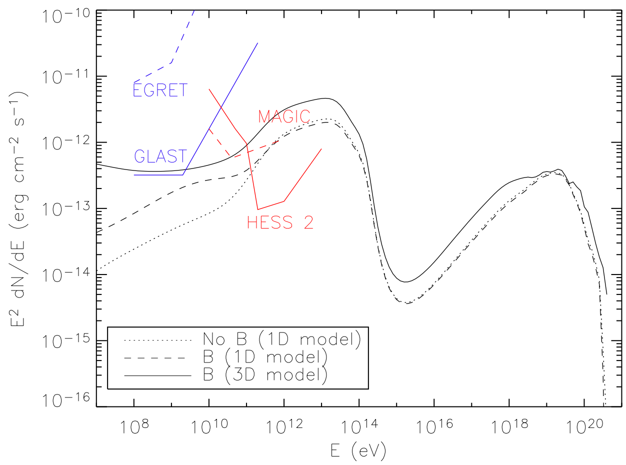

FIGURE 2. Differential γ-ray fluxes (multiplied by squared energy) from electromagnetic cascades including synchrotron radiation, initiated by photo-pion and pair production by protons injected with an $E^{-2.7}$ spectrum (not shown) by a source at distance $d = 20\,\mathrm{Mpc}$. We assume the source contributes a fraction $\simeq 0.2$ to the total UHECR flux, corresponding to a proton luminosity $\simeq 4\times10^{42}\,\mathrm{erg\,s}^{-1}$ above $10^{19}\,\mathrm{eV}$. A structured magnetic field of 0.1–$1\,\mu\mathrm{G}$ extends a few Mpc around the source in case of the 1D and 3D simulations which take into account synchrotron radiation of electrons and positrons. The 1D model neglects proton deflection whereas the 3D simulation follows 3-dimensional proton trajectories. The latter case implies that the fluxes shown here would be extended over $\sim 5^\circ(20\,\mathrm{Mpc}/d)$ on the sky. The fluxes are comparable to sensitivities of space-based γ−ray (blue) and ground-based imaging air Čerenkov detectors (red).

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